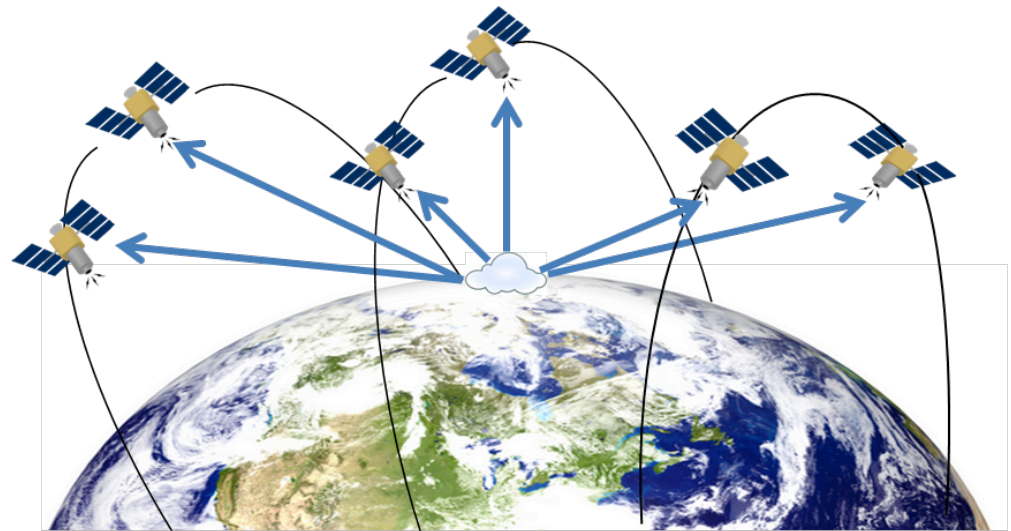
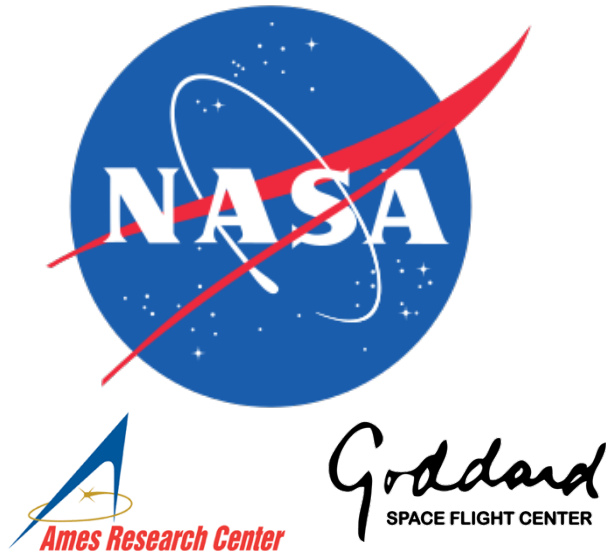


Aerosol remote sensing with small satellites in formation flight

Kirk Knobelspiesse¹ and Sreeja Nag

NASA Goddard Space Flight Center and NASA Ames Research Center



1 funding generously provided by the NASA New (Early Career) Investigator Program in Earth Science

Synopsis

Motivation potential of small satellite formations

Background

- Coupled Model Based Systems Engineering (MBSE) +
- Information content based Observing System Simulation Experiment (OSSE)

Approach

- Transform prior BRDF analysis for aerosol remote sensing
- Information content analysis details - sensor and simulations

Results

- Example BRDF results. Example Jacobian BRDF
- Degrees of Freedom
- Relative Aerosol Optical Thickness predicted uncertainty
- Fine mode effective radius predicted uncertainty

Conclusions

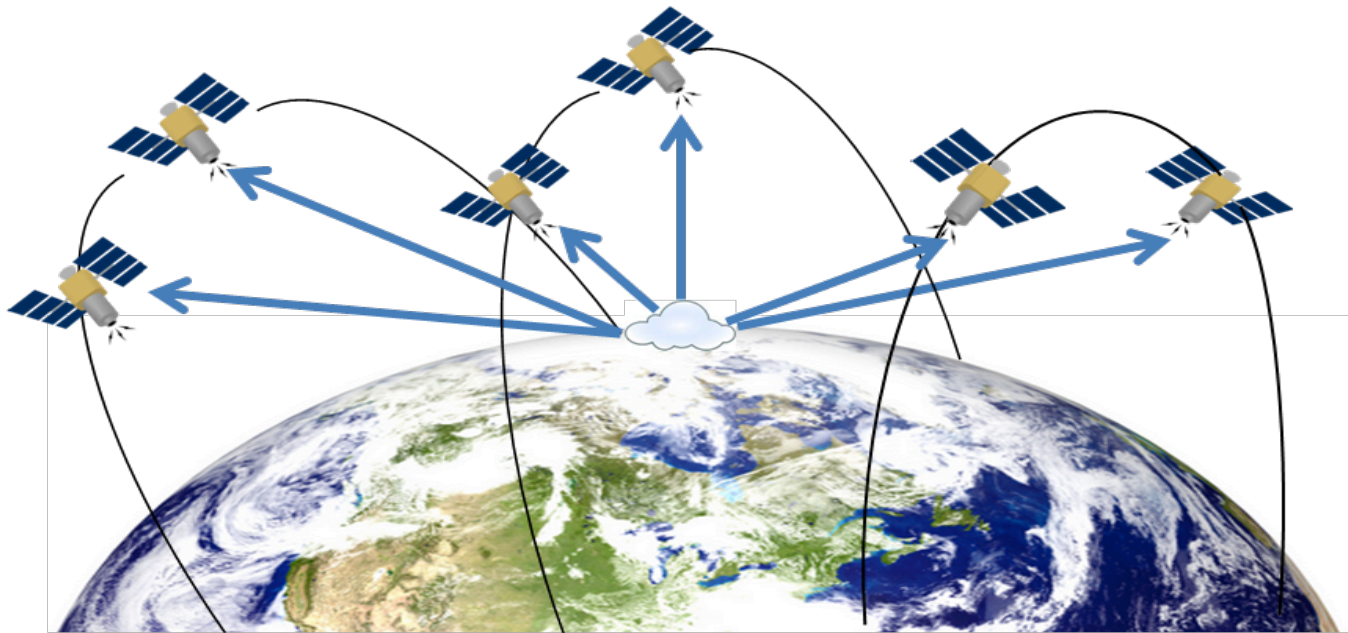
Formation flight – *alternate aerosol remote sensing paradigm?*

We need more information: *multiple spectra, multiple view angles, multiple polarization states*

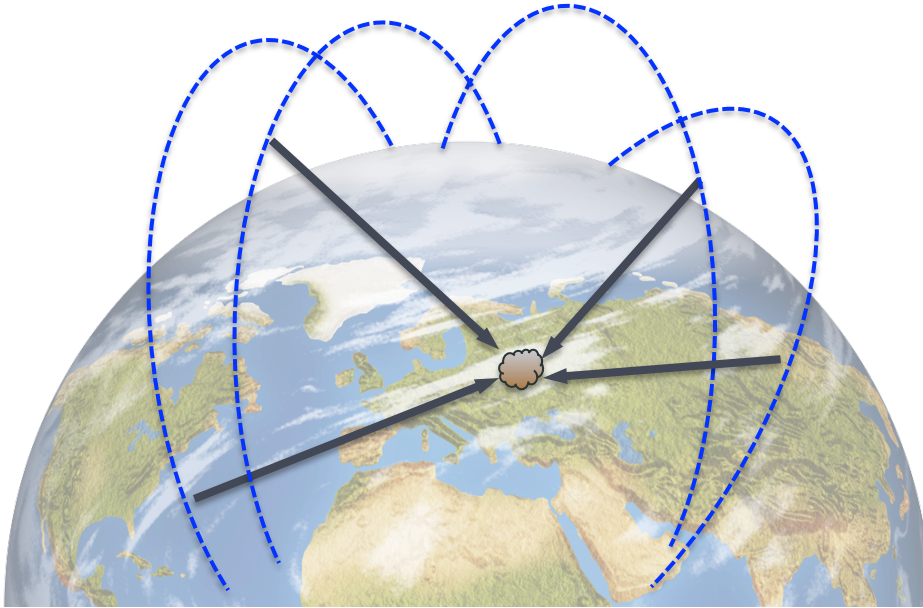
So far, we've put this all on a single instrument/platform

New cube/small satellite technology means observation can be dispersed...

... can there be a benefit to doing this?

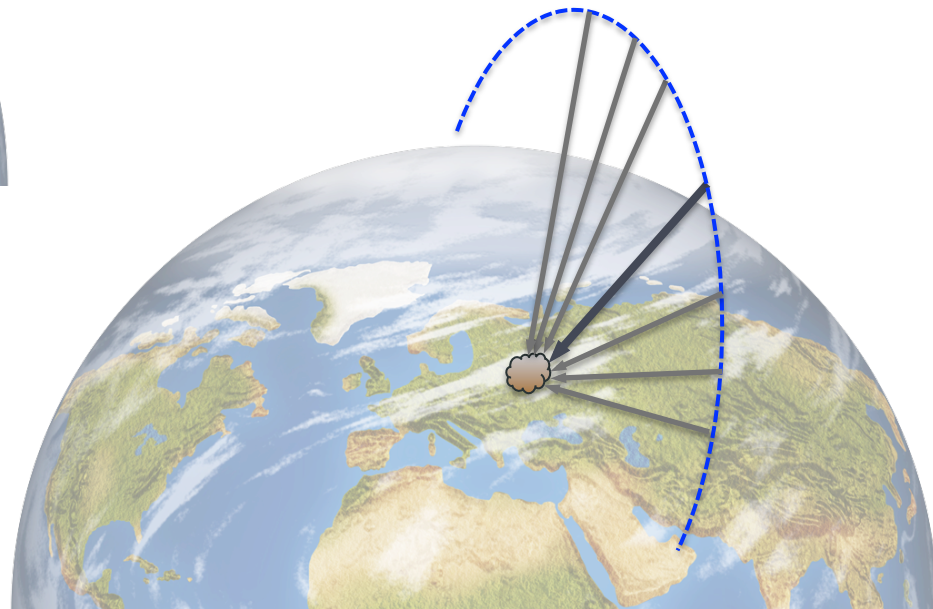


Formation flight: access alternate view geometries



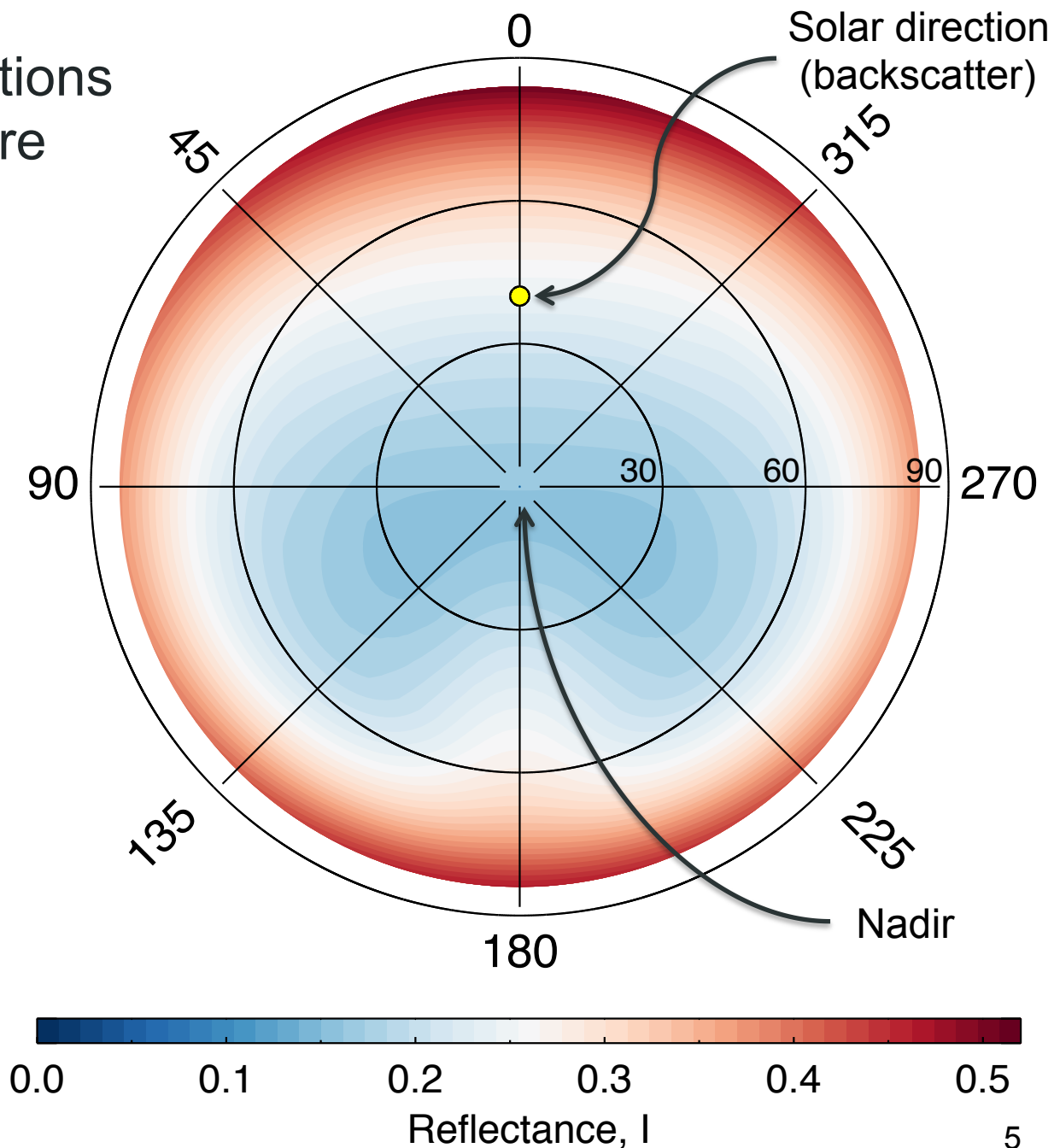
Distributed viewing geometry:
Independent spacecraft observe a common location, variety of view zenith, azimuth angles

Single spacecraft
Multiple views in one plane



Multi-angle observations
at Top of Atmosphere
(TOA) *sample* the:

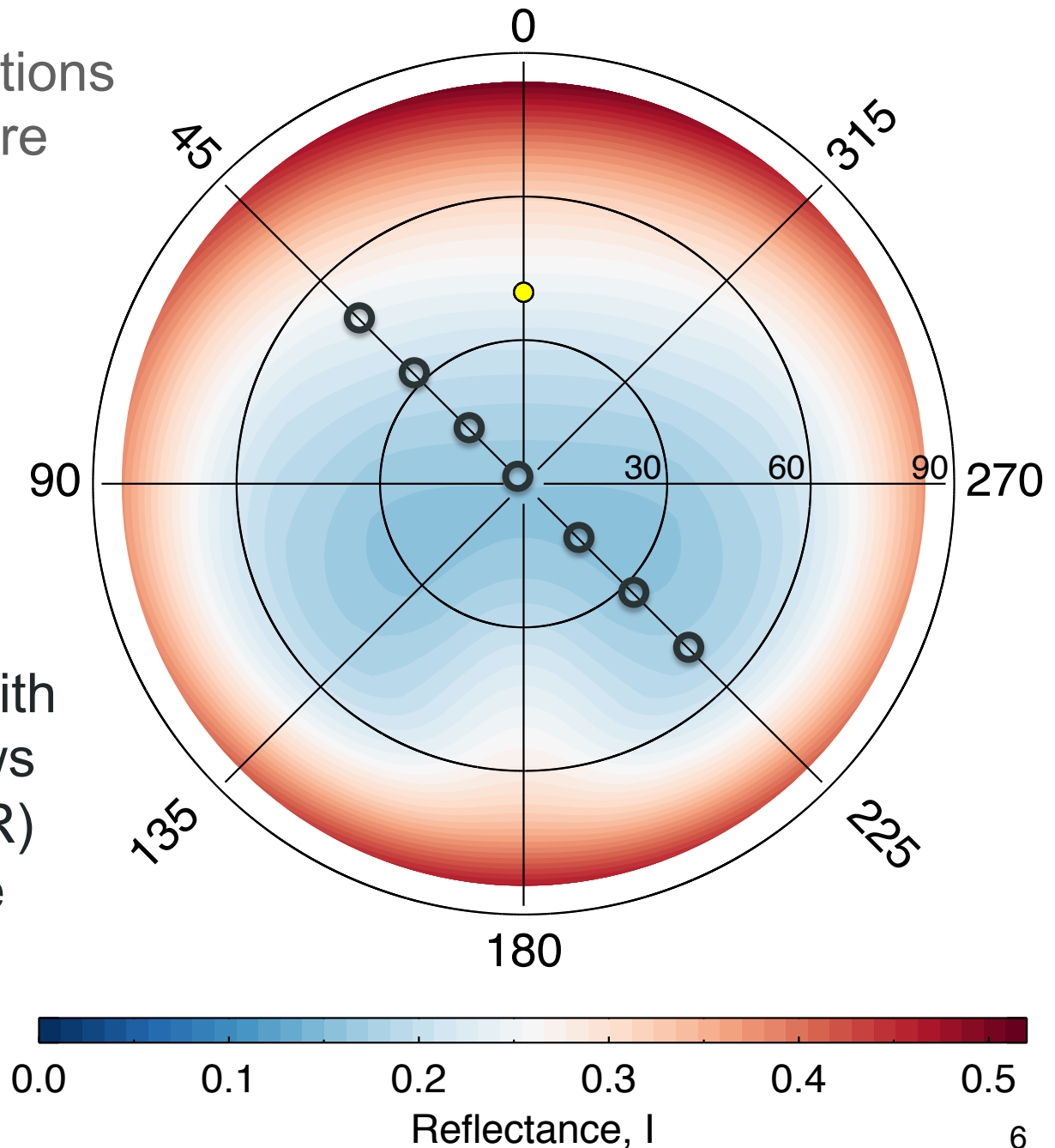
total Bidirectional
Reflectance
Distribution
Function (BRDF)



Multi-angle observations
at Top of Atmosphere
(TOA) *sample* the:

total Bidirectional
Reflectance
Distribution
Function (BRDF)

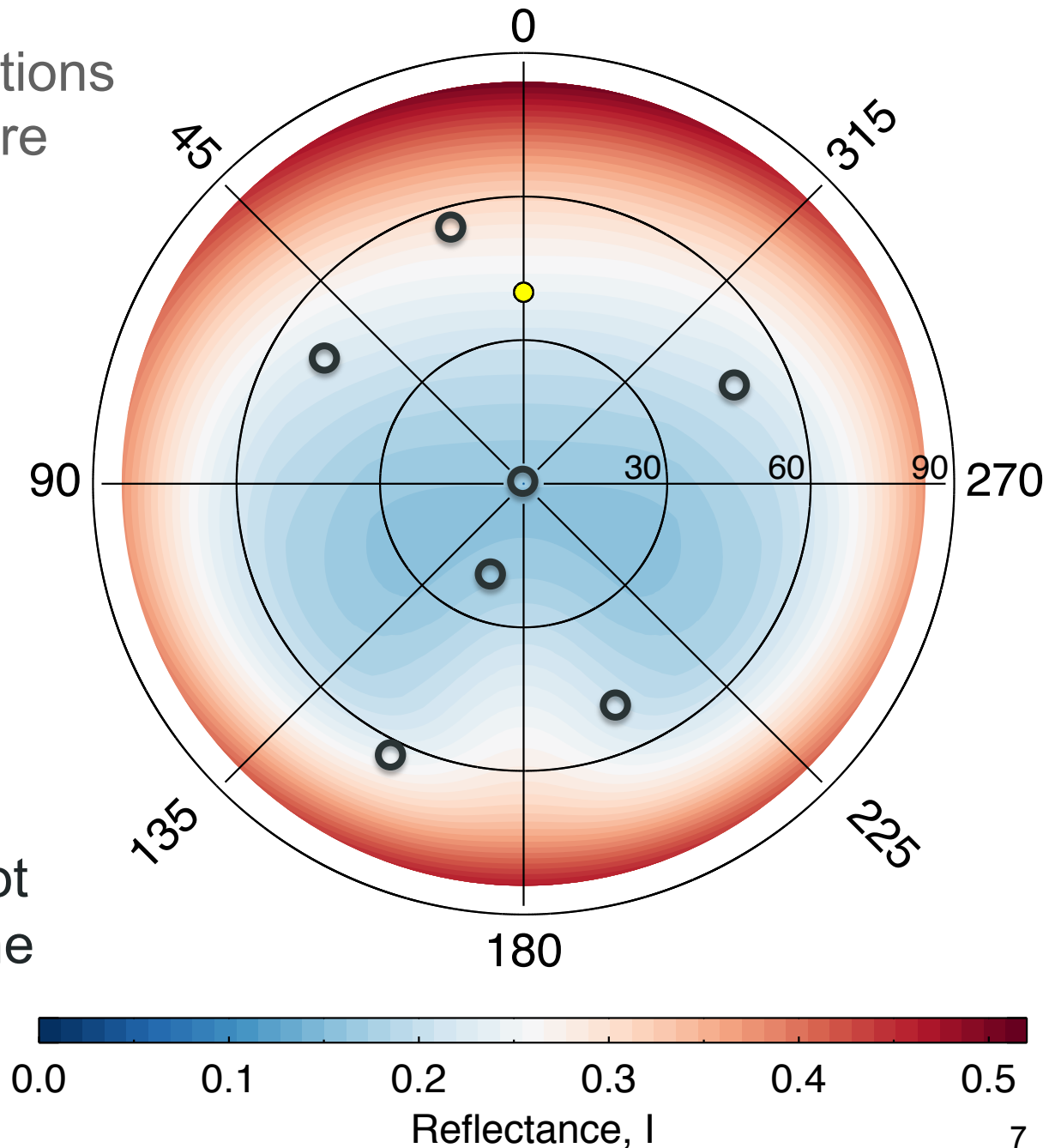
“single” platforms with
multiple angle views
(ie POLDER, MISR)
sample in a plane



Multi-angle observations
at Top of Atmosphere
(TOA) *sample* the:

total Bidirectional
Reflectance
Distribution
Function (BRDF)

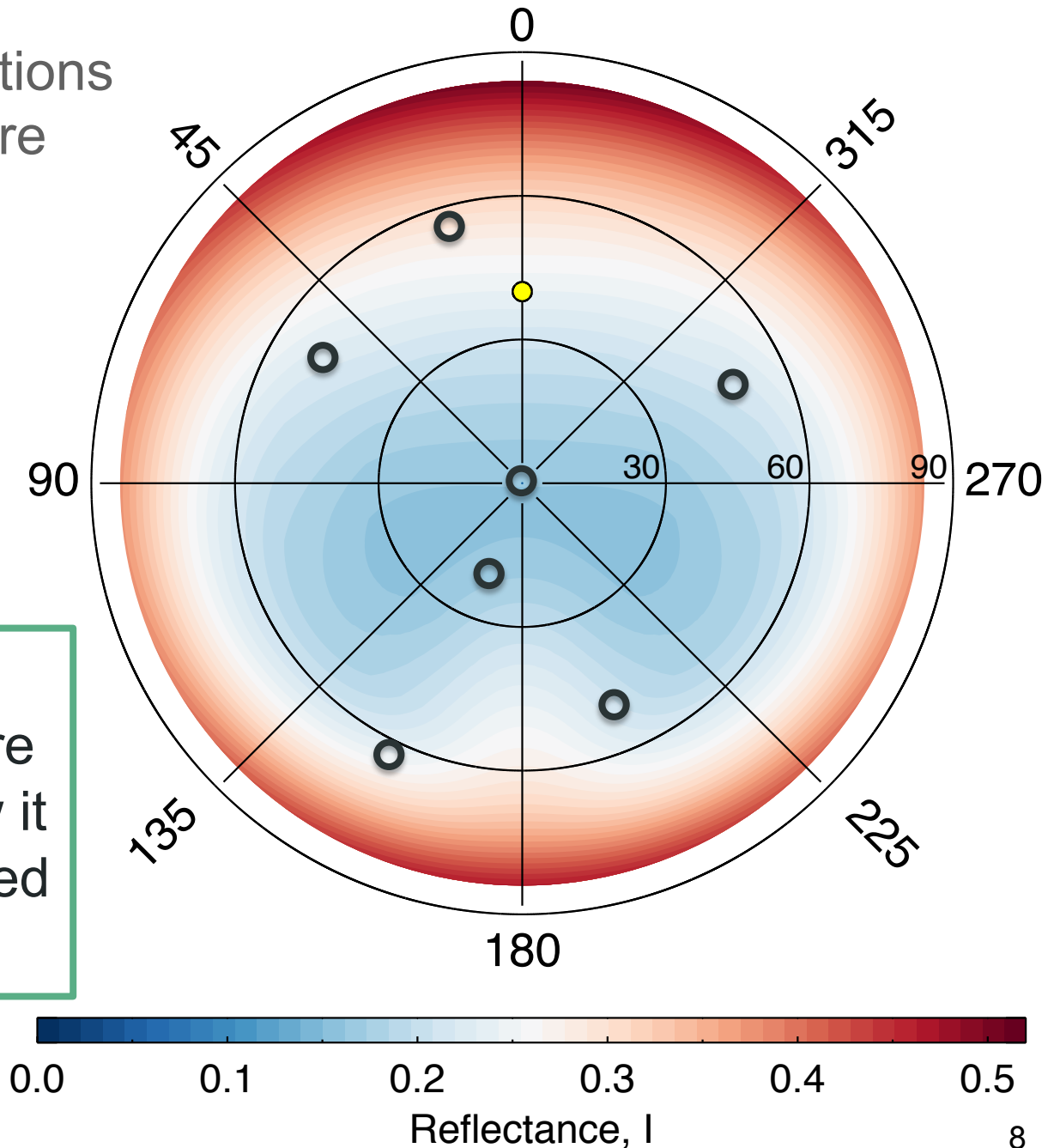
Samples from
constellations of
(single view)
instruments are not
restricted to a plane



Multi-angle observations
at Top of Atmosphere
(TOA) *sample* the:

total Bidirectional
Reflectance
Distribution
Function (BRDF)

Is this useful?
Depends on nature
of BRDF, and how it
incorporates desired
information



Conversion of Sreeja Nag's analysis for surface BRDF remote sensing to aerosol remote sensing



Contents lists available at [ScienceDirect](http://www.sciencedirect.com)

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag



Observing system simulations for small satellite formations estimating bidirectional reflectance



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ARTICLE INFO

Article history:

Received 1 November 2014

Accepted 30 April 2015

Available online 4 September 2015

Keywords:

Multi-angular remote sensing

Small satellite

Formation

BRDF

OSSE

ABSTRACT

The bidirectional reflectance distribution function (BRDF) gives the reflectance of a target as a function of illumination geometry and viewing geometry, hence carries information about the anisotropy of the surface. BRDF is needed in remote sensing for the correction of view and illumination angle effects (for example in image standardization and mosaicing), for deriving albedo, for land cover classification, for cloud detection, for atmospheric correction, and other applications. However, current spaceborne instruments provide sparse angular sampling of BRDF and airborne instruments are limited in the spatial and temporal coverage. To fill the gaps in angular coverage within spatial, spectral and temporal require-

Nag, S., C.K. Gatebe, O. de Weck, **Observing system simulations for small satellite formations estimating bidirectional reflectance**, *Int. J. of Applied Earth Observation and Geoinformation*, 43, Dec. 2015, pp 102-118.

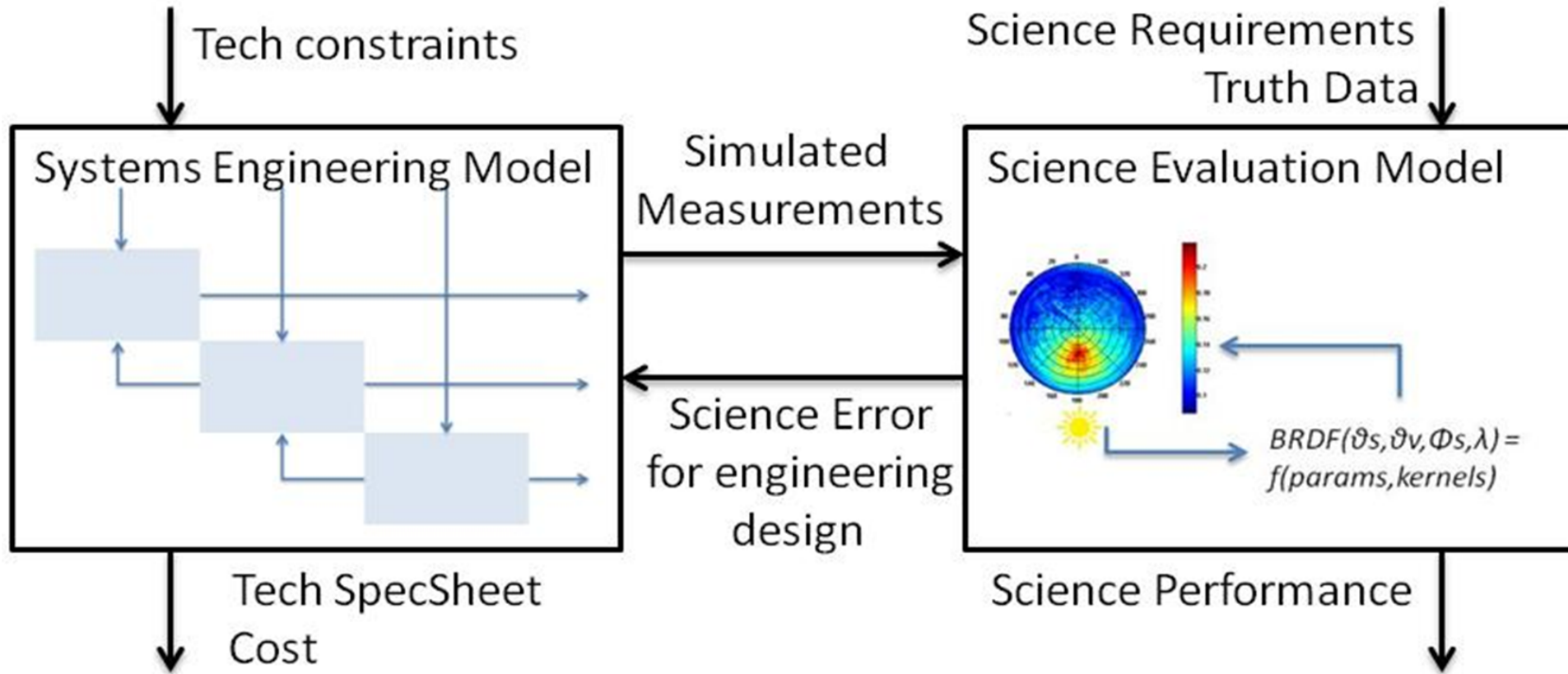
Nag, S., C.K. Gatebe, D.W. Miller, O. de Weck, **Effect of satellite formations and imaging modes on global albedo estimation**, *Acta Astronautica*, 126, Sept. 2016, pp. 77-97.

Nag, S., C.K. Gatebe, T. Hilker, **Simulation of Bidirectional Reflectance-Distribution Function Measurements using Small Satellite Formations**, *IEEE J. of Selected Topics in Applied Earth Observations and Remote Sensing*, accepted in April 2016, in press

possible.

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Coupled Model Based Systems Engineering (MBSE) and Observing System Simulation Experiment (OSSE) tools



MBSE model predicted orbit geometries

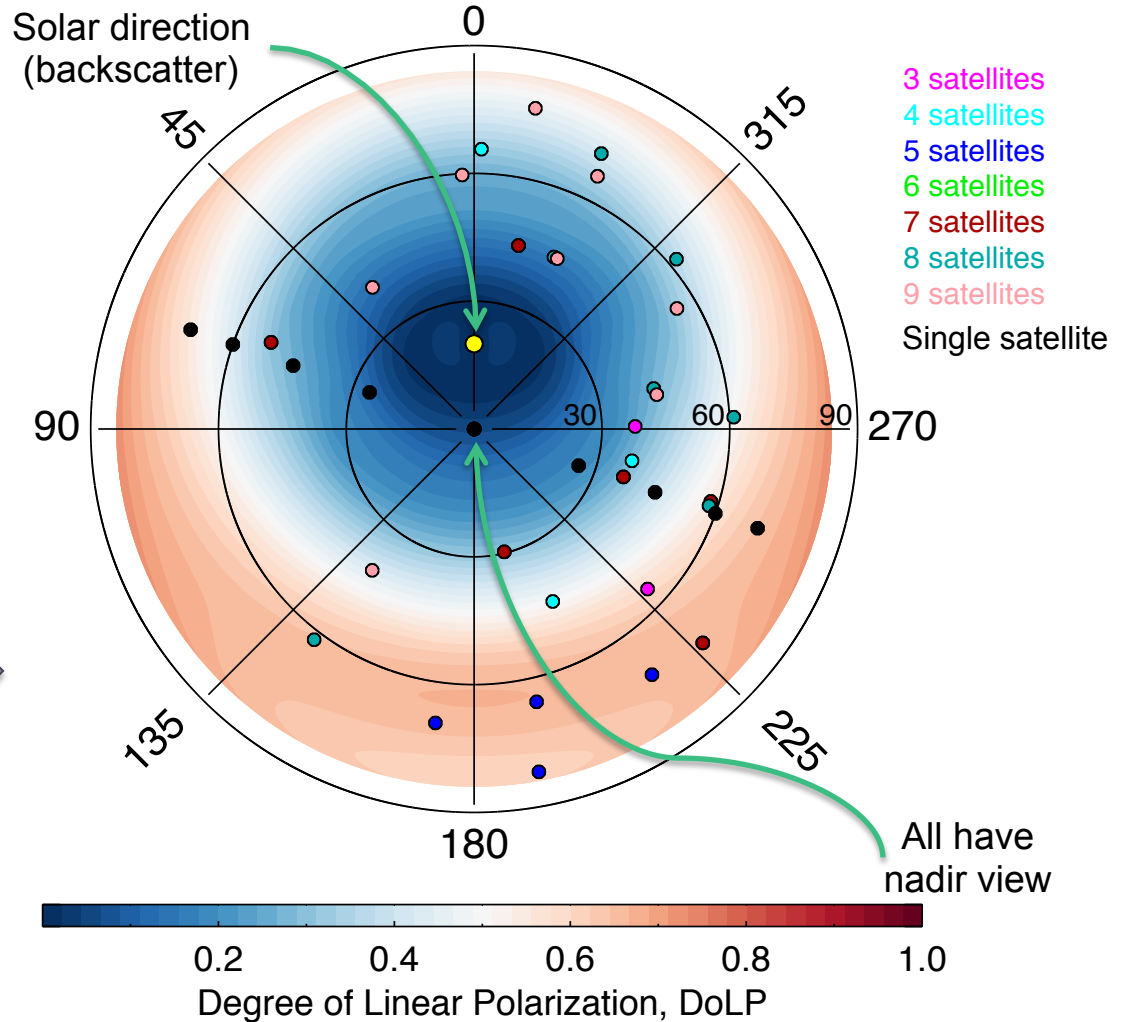
MBSE model predicts 8 different configurations

- 3 through 9 satellites flying in formation, tracking nadir observing satellite
- 9 view angle single satellite

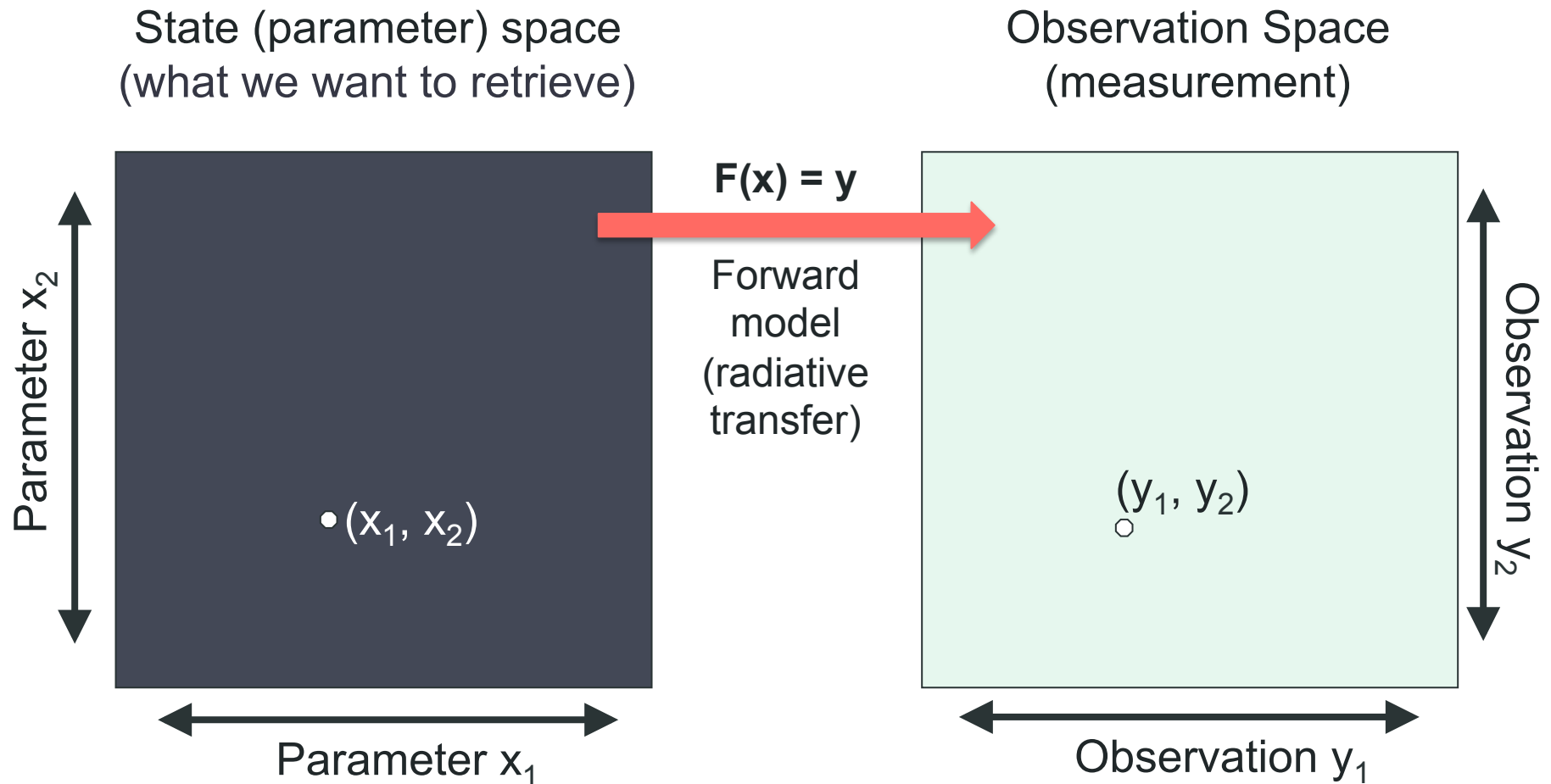
Geometries for 100+ daytime observations

Example of a single observation →

Maritime-ocean, AOD=0.25, 555nm, SZA=20, DoLP



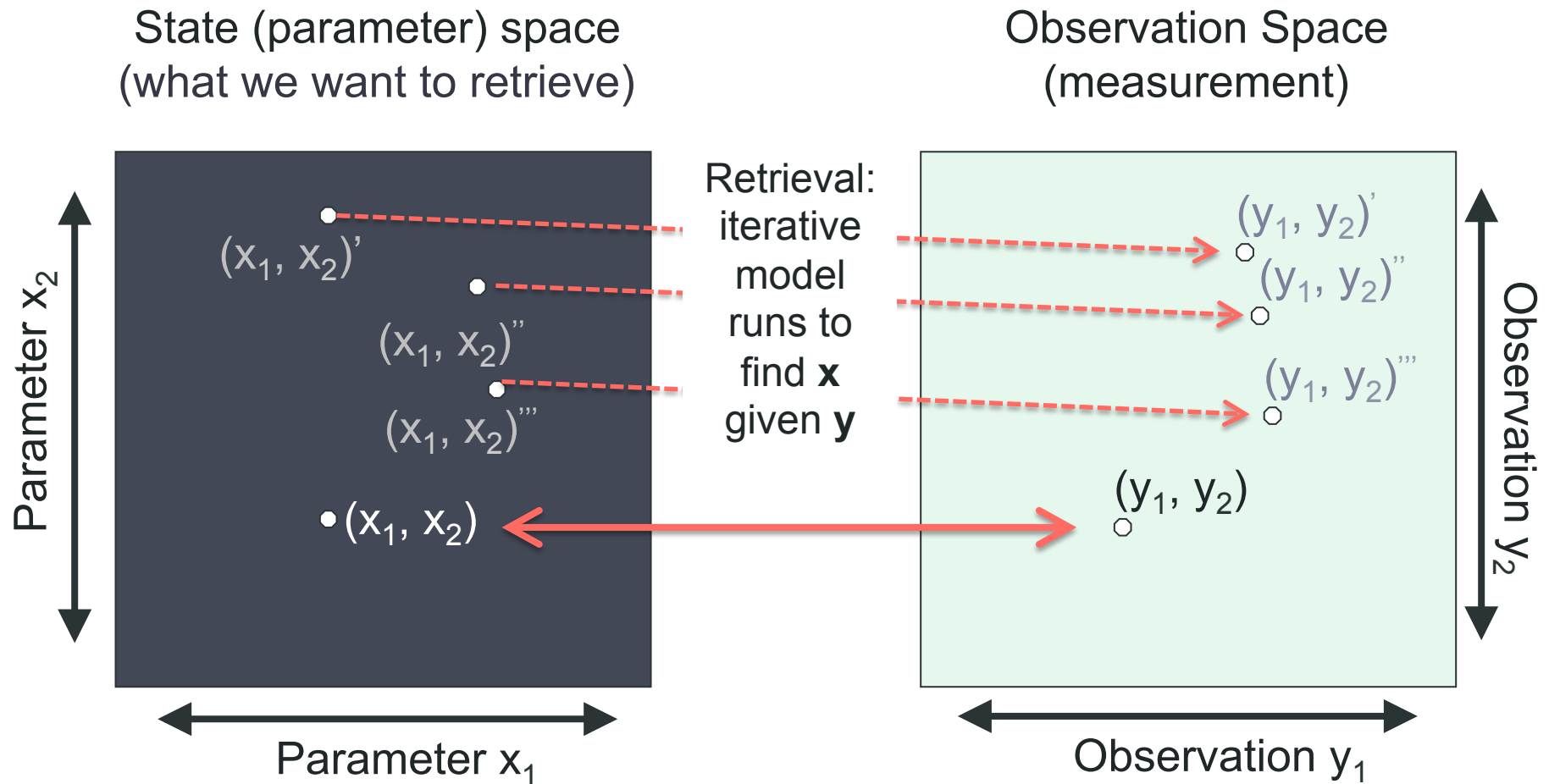
OSSE: information content assessment



Knobelspiesse, K. et al. (2012) Analysis of fine-mode aerosol retrieval capabilities by different passive remote sensing instrument designs *Optics Express*, 20 (19).

Rodgers, C. D. (2000). Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific, Singapore.

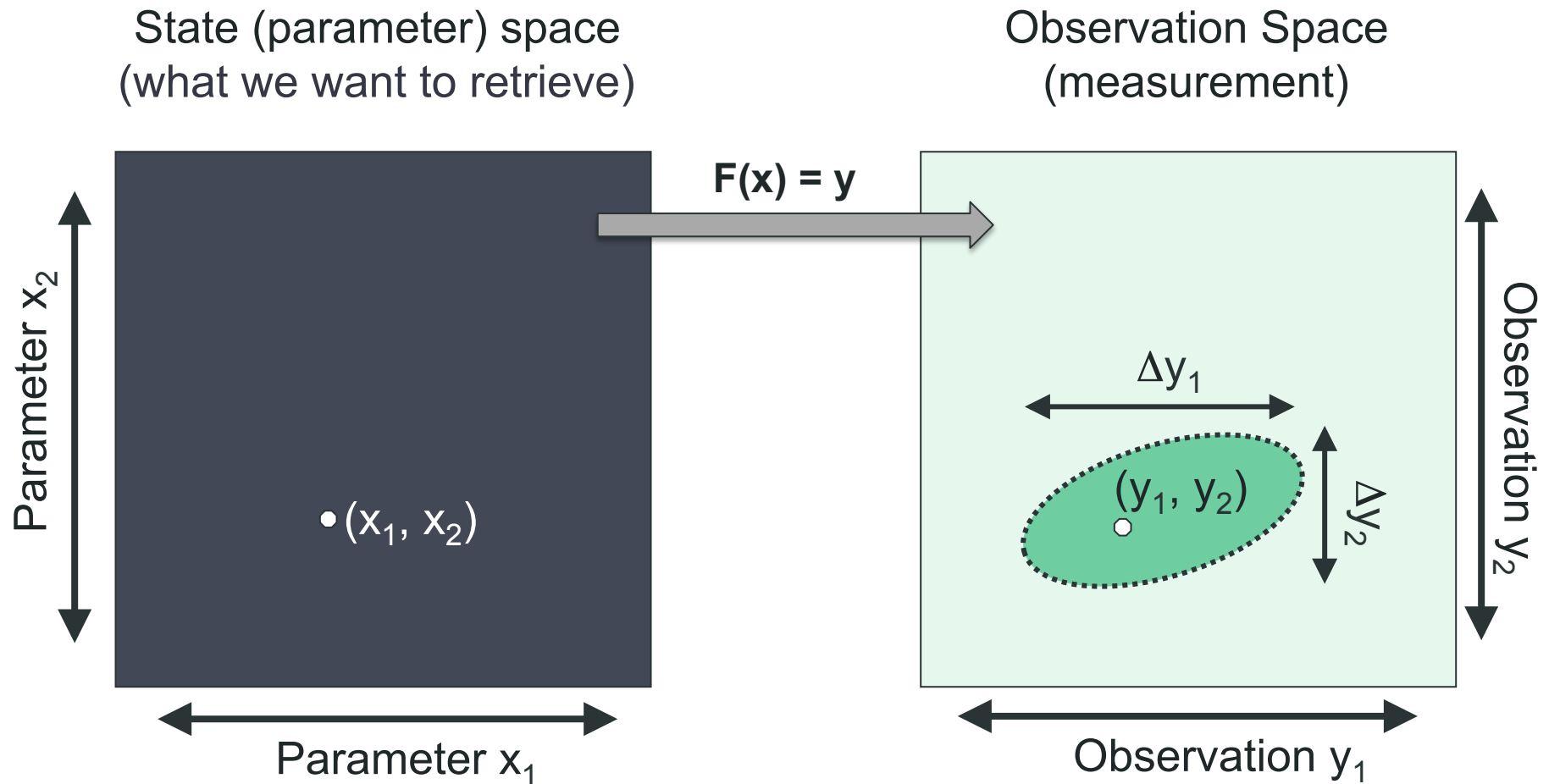
OSSE: information content assessment



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Rodgers, C. D. (2000). Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific, Singapore.

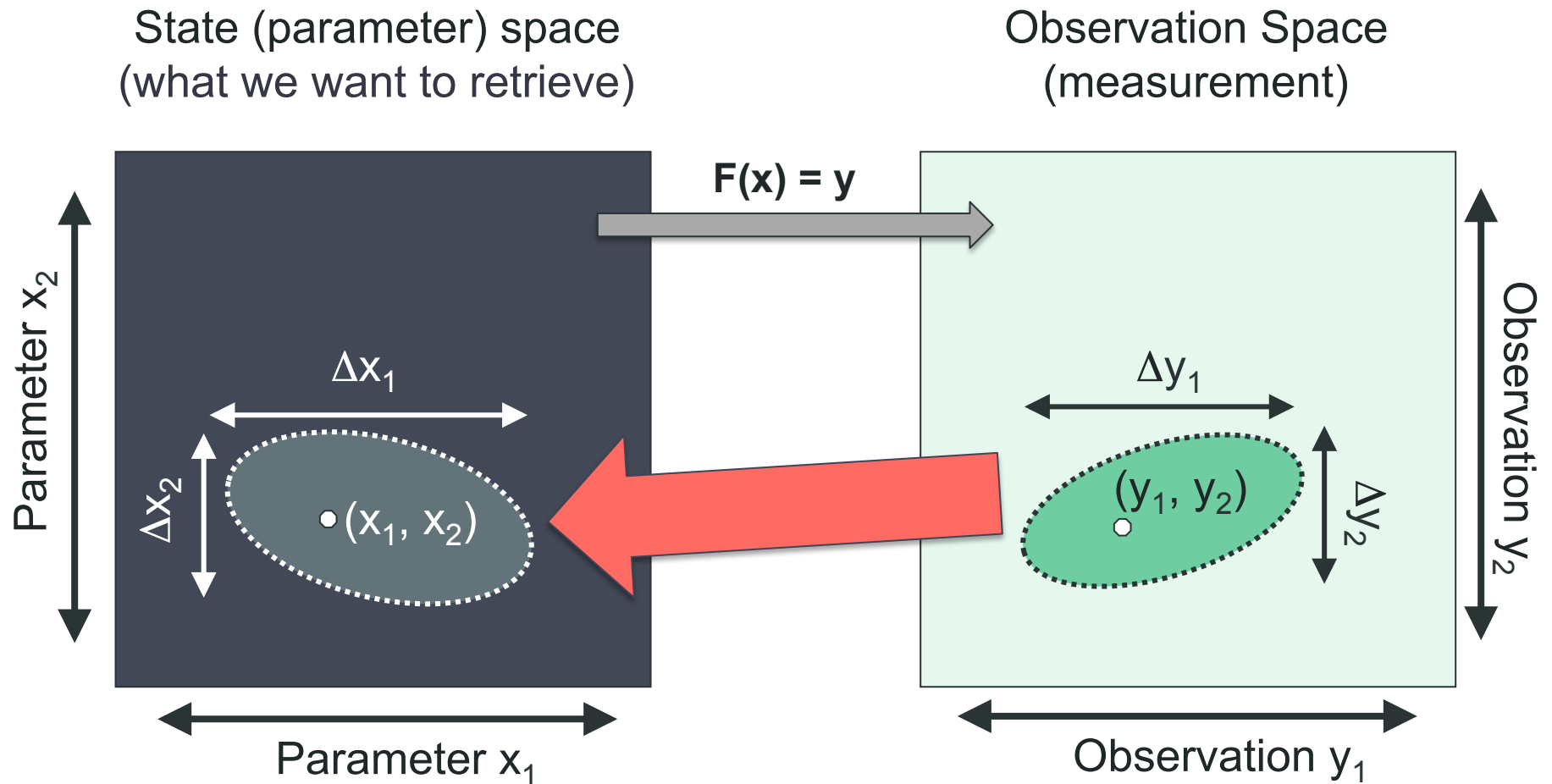
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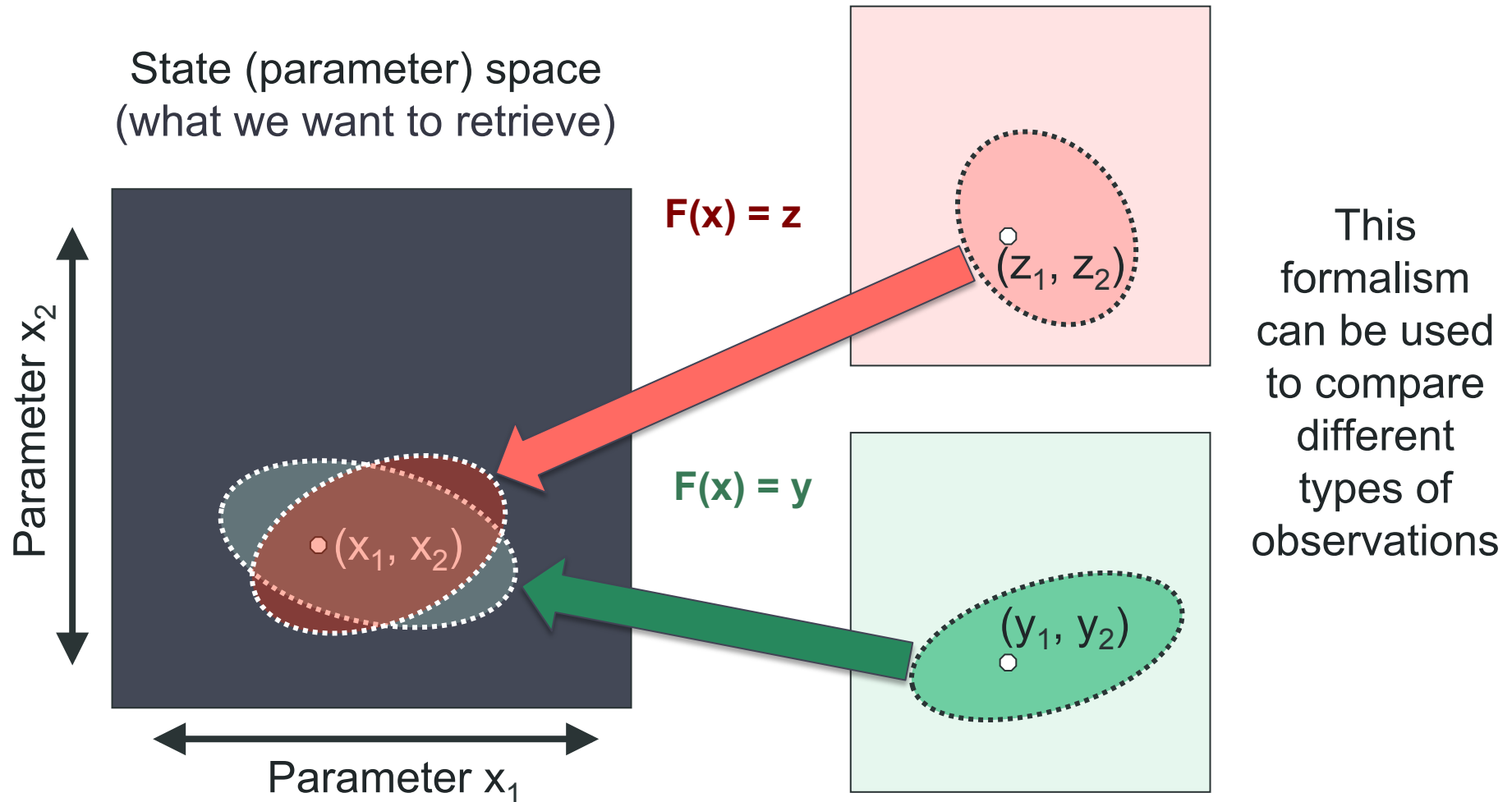
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Rodgers, C. D. (2000). Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific, Singapore.

OSSE: Information content assessment

Jacobian matrix: model
calculated parameter sensitivity

$$K_{i,j} = \partial F_i(x) / \partial x_j$$

**Measurement error
covariance matrix:** how
we specify instrument
characteristics

A priori matrix:
parameter knowledge
before observation

$$\hat{S} = \left[K^T S_{\varepsilon}^{-1} K + S_a^{-1} \right]^{-1}$$

Retrieval error covariance matrix: expected
parameter uncertainty, overall metrics for info
such as degrees of freedom

Degrees of Freedom (DoF) for signal

$$d_s = \text{trace} \left(\left[K^T S_{\varepsilon}^{-1} K + S_a^{-1} \right]^{-1} K^T S_{\varepsilon}^{-1} K \right)$$

“Essentially, all models are wrong, but some are useful” – George Box

OSSE: Information content assessment

“Essentially, all models are wrong, but some are useful” – George Box

Caveats

This method predicts retrieval uncertainty for a system with

- Perfect knowledge of observation uncertainty
- Perfect radiative transfer (forward) model
- Perfect ability to retrieve solution from observation



And we
are far
from
perfect!

The results can be considered a ‘**best case scenario**’

Measurement system **can’t do better than this** without adding information (such as constraints)

Considers an **unconstrained** retrieval over free parameters

This is a powerful technique for **relative** comparisons between measurement systems – assumptions are uniform

Simulation approach

Simulated instrument characteristics

Common to all

Wavelengths: 0.35, 0.41, 0.555, 0.865, 2.25 μm

Radiometric uncertainty: 3%, polarimetric uncertainty: 0.5%

Radiometers

- multi-angle (9) vs. distributed single view (3-9)

Polarimeters

- multi-angle (9) vs. distributed single view (3-9)

(16 observation systems in total)

Simulated scenes (based on AERONET, Dubovik et al 2002)

Maritime aerosol over an open ocean, AOT(555nm) = 0.05, 0.15, 0.25

Aerosol: Fraction of AOT(555nm) in fine mode: 36%

Refractive index: 1.37-i0.001

Fine size mode: $r_{\text{eff}}=0.135\mu\text{m}$, $v_{\text{eff}}=0.193$

Coarse size mode: $r_{\text{eff}}=3.36\mu\text{m}$, $v_{\text{eff}}=0.704$

Ocean: Chlorophyll-a = 0.03 mg/m³, Wind Speed = 8 m/s

**6 retrieval
parameters**

Greenbelt aerosol over sparse vegetation, AOT(555nm) = 0.05, 0.15, 0.25

Aerosol: Fraction of AOT(555nm) in fine mode: 90%

Refractive index: 1.40-i0.003

Fine size mode: $r_{\text{eff}}=0.170\mu\text{m}$, $v_{\text{eff}}=0.155$

Coarse size mode: $r_{\text{eff}}=5.52\mu\text{m}$, $v_{\text{eff}}=0.755$

Ground: surface BRDF specified by 3 spectrally invariant kernels (fresnel, volumetric geometric) + spectrally varying isotropic values (5)

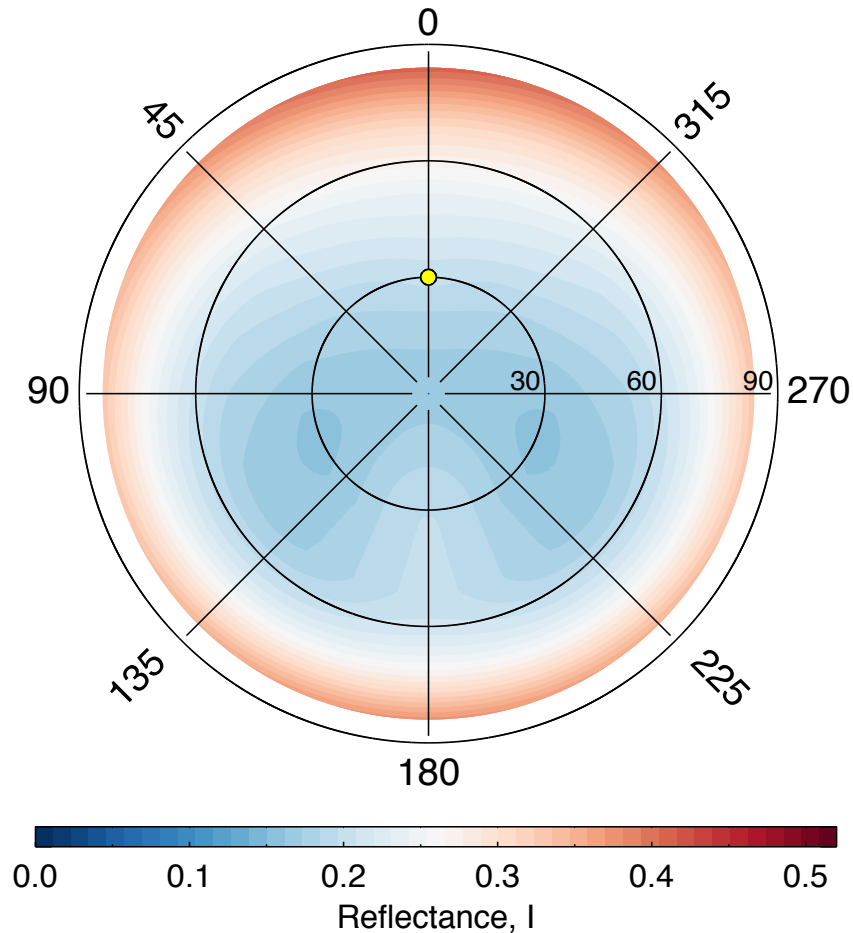
**12 retrieval
parameters**

(6 scenes x 16 observation systems x 100+ geometries)

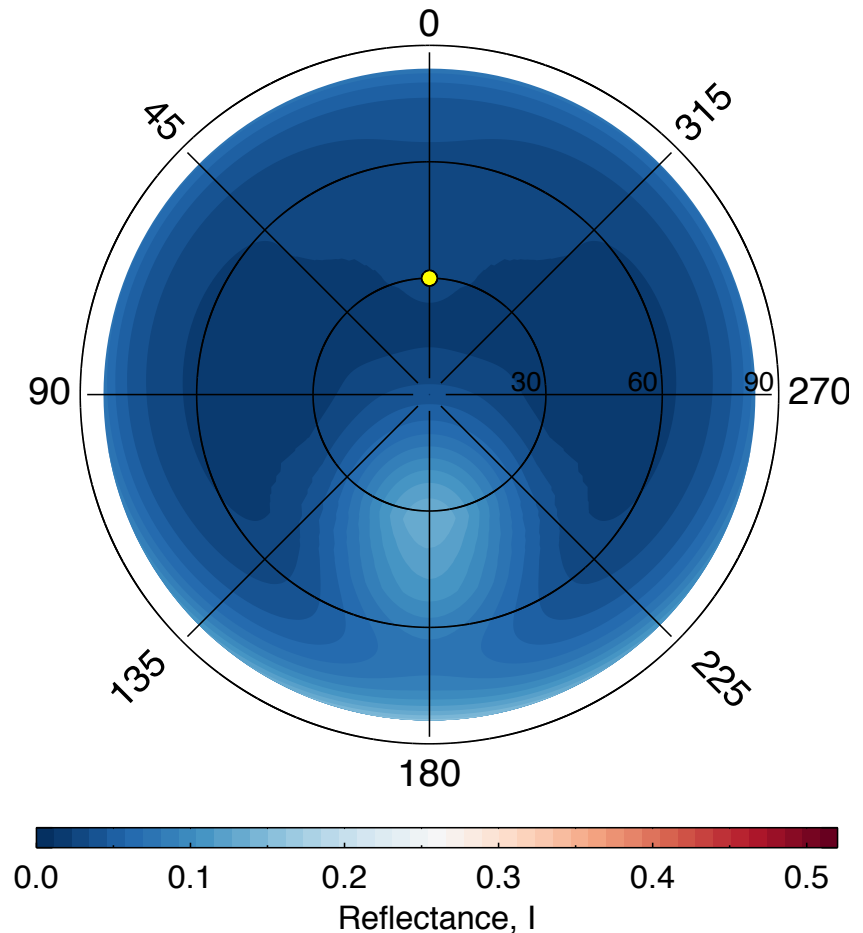
Simulation results

Maritime scene, AOT(555nm)=0.15, reflectance

Maritime-ocean, AOD=0.15, 410nm, SZA=30, I

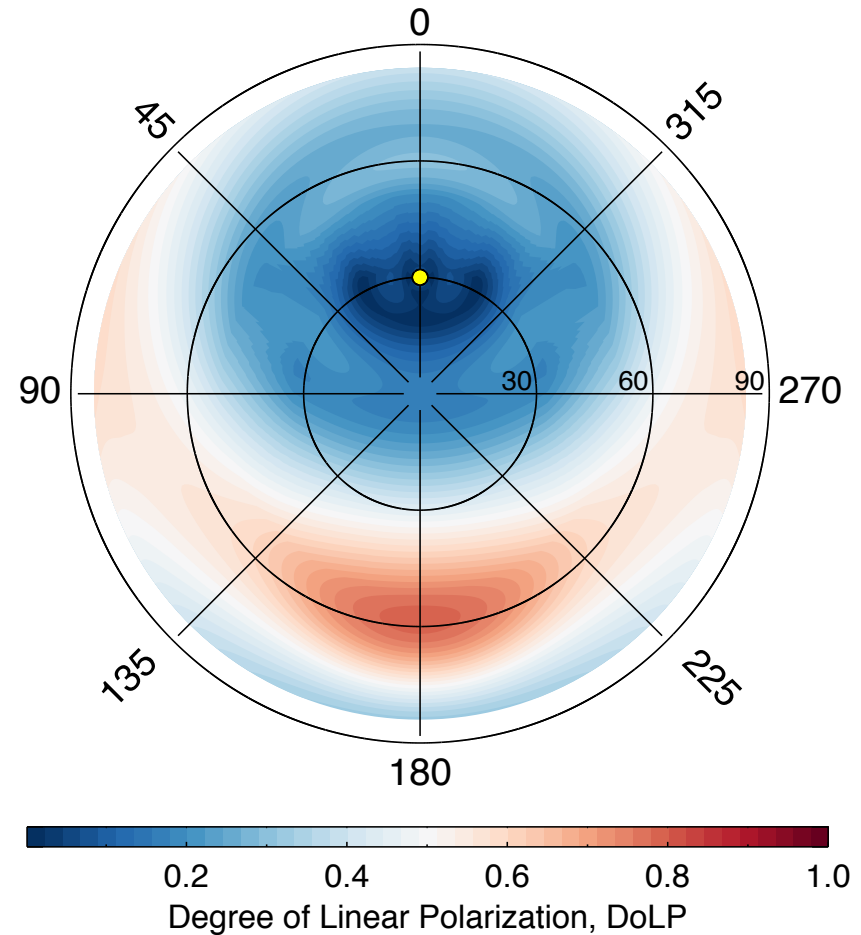
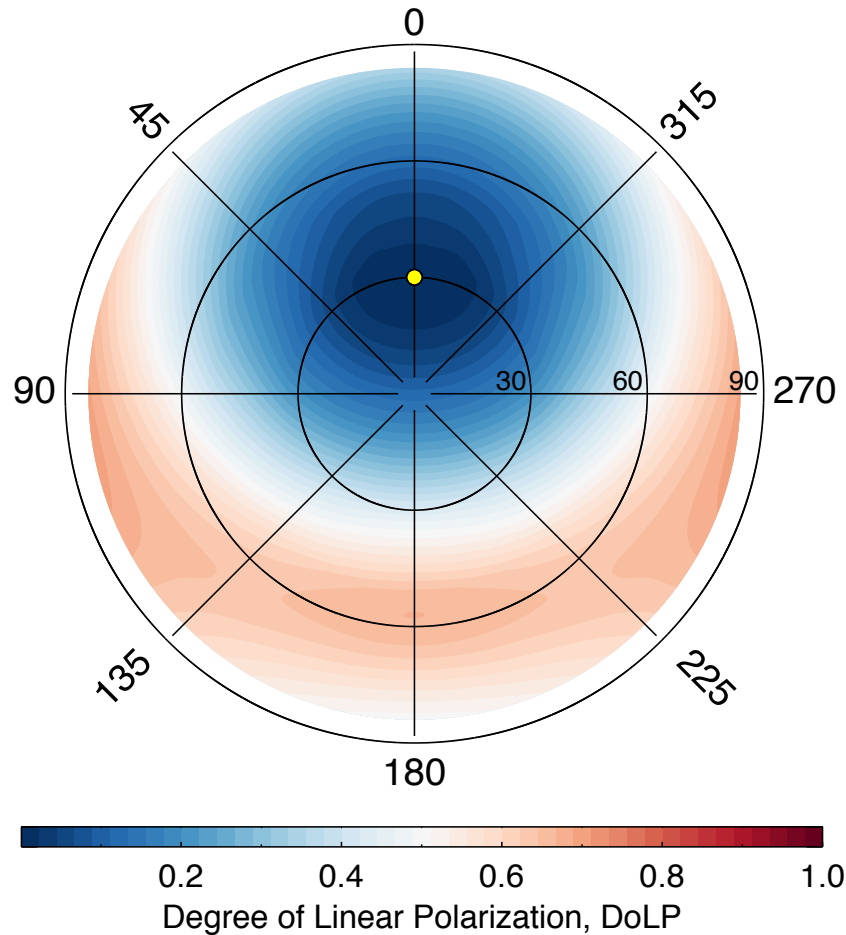


Maritime-ocean, AOD=0.15, 865nm, SZA=30, I



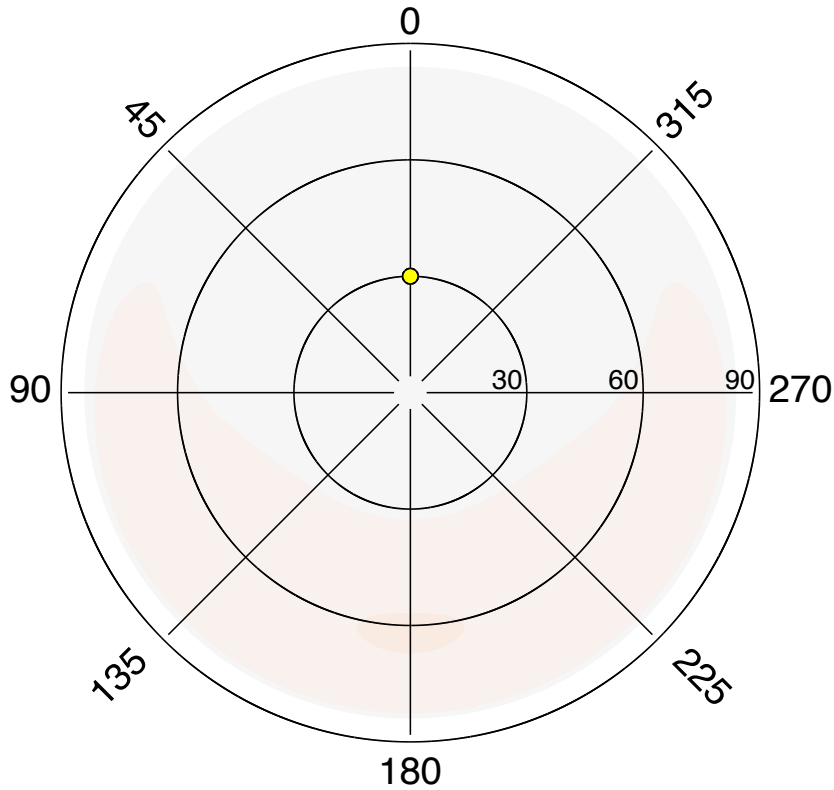
Maritime scene, AOT=0.15, Degree of Linear Polarization (DoLP)

Maritime-ocean, AOD=0.15, 410nm, SZA=30, DoLP Maritime-ocean, AOD=0.15, 865nm, SZA=30, DoLP



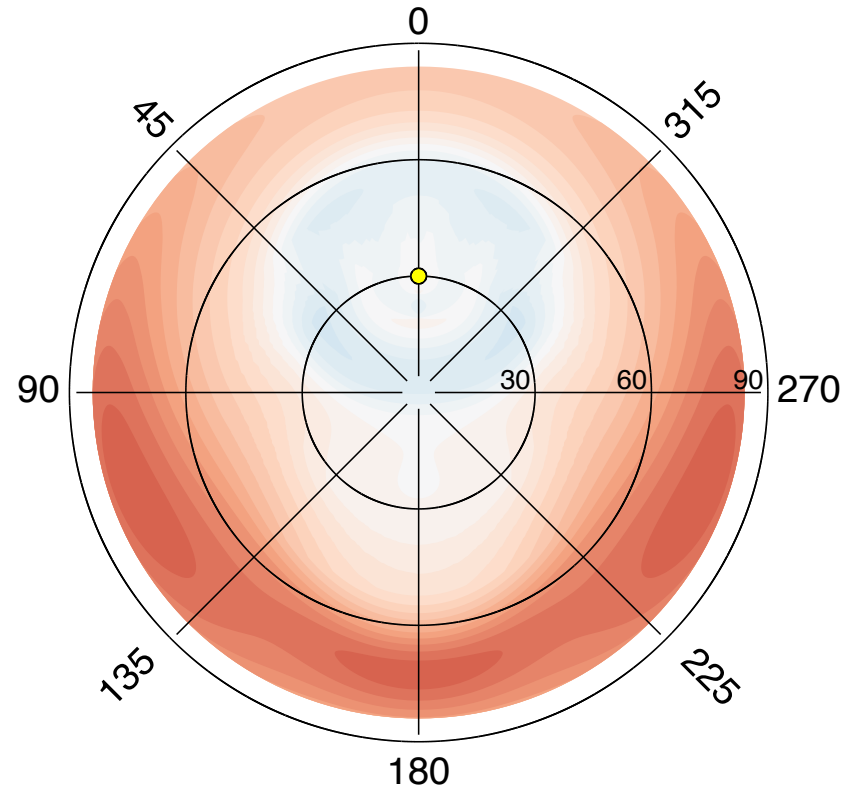
Maritime scene, AOT=0.15, Jacobian (DoLP)

DoLP Jacobian: 410nm coarse mode AOT



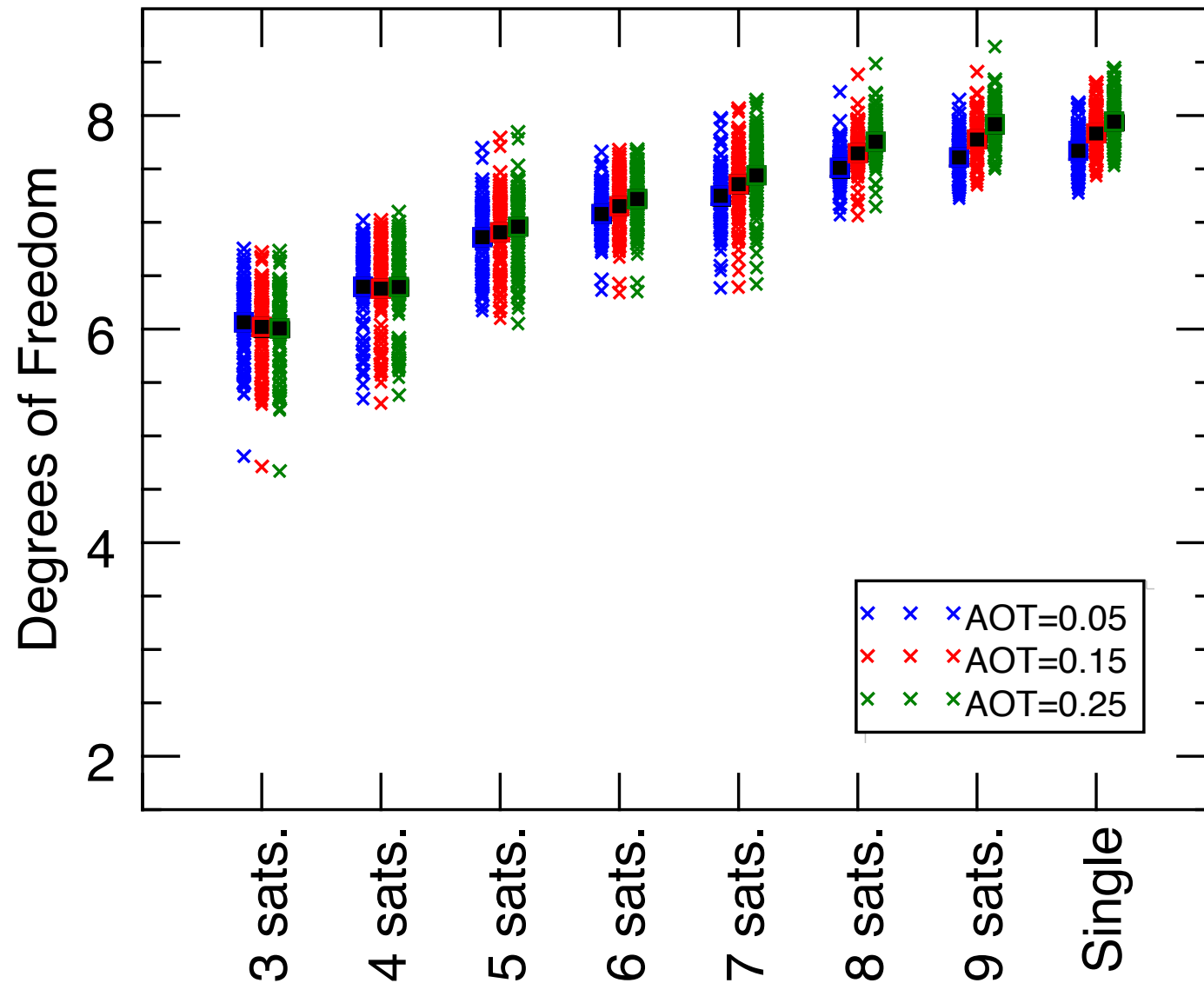
-3 -2 -1 0 1 2 3
Sensitivity in Degree of Linear Polarization, DoLP

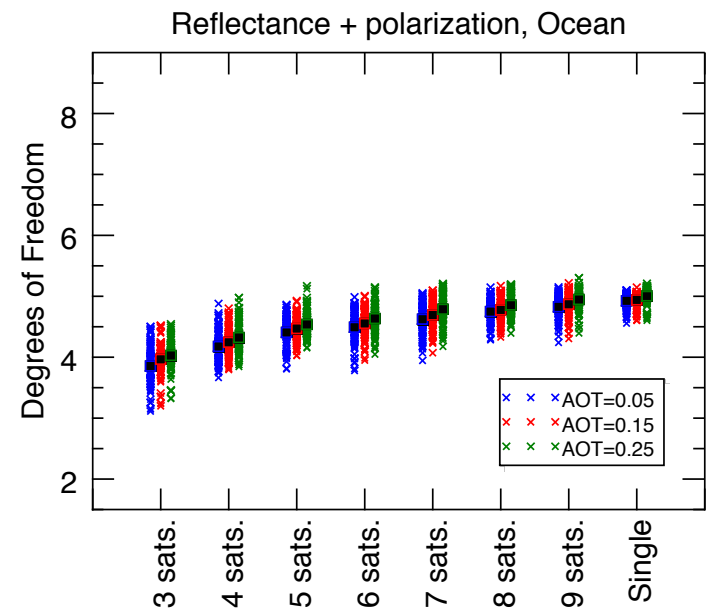
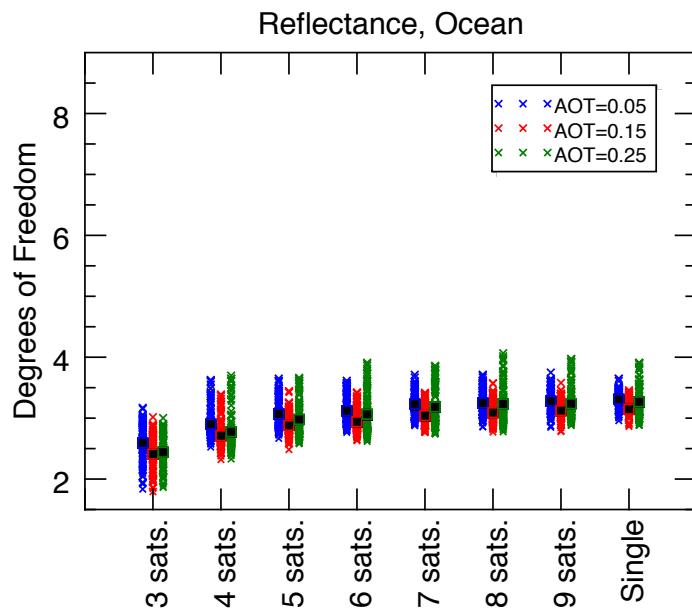
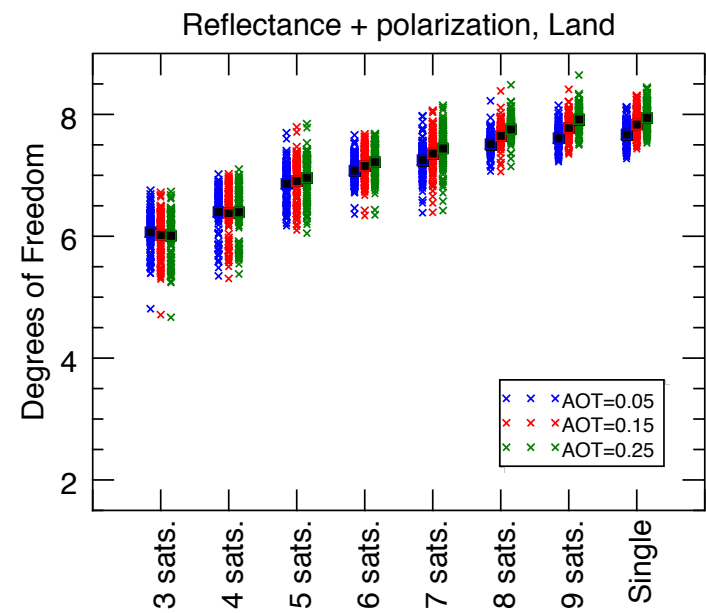
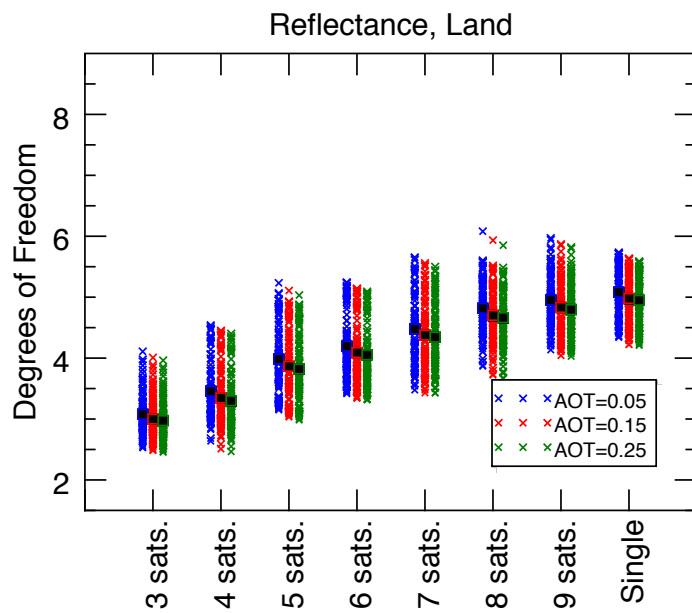
DoLP Jacobian: 865nm coarse mode AOT



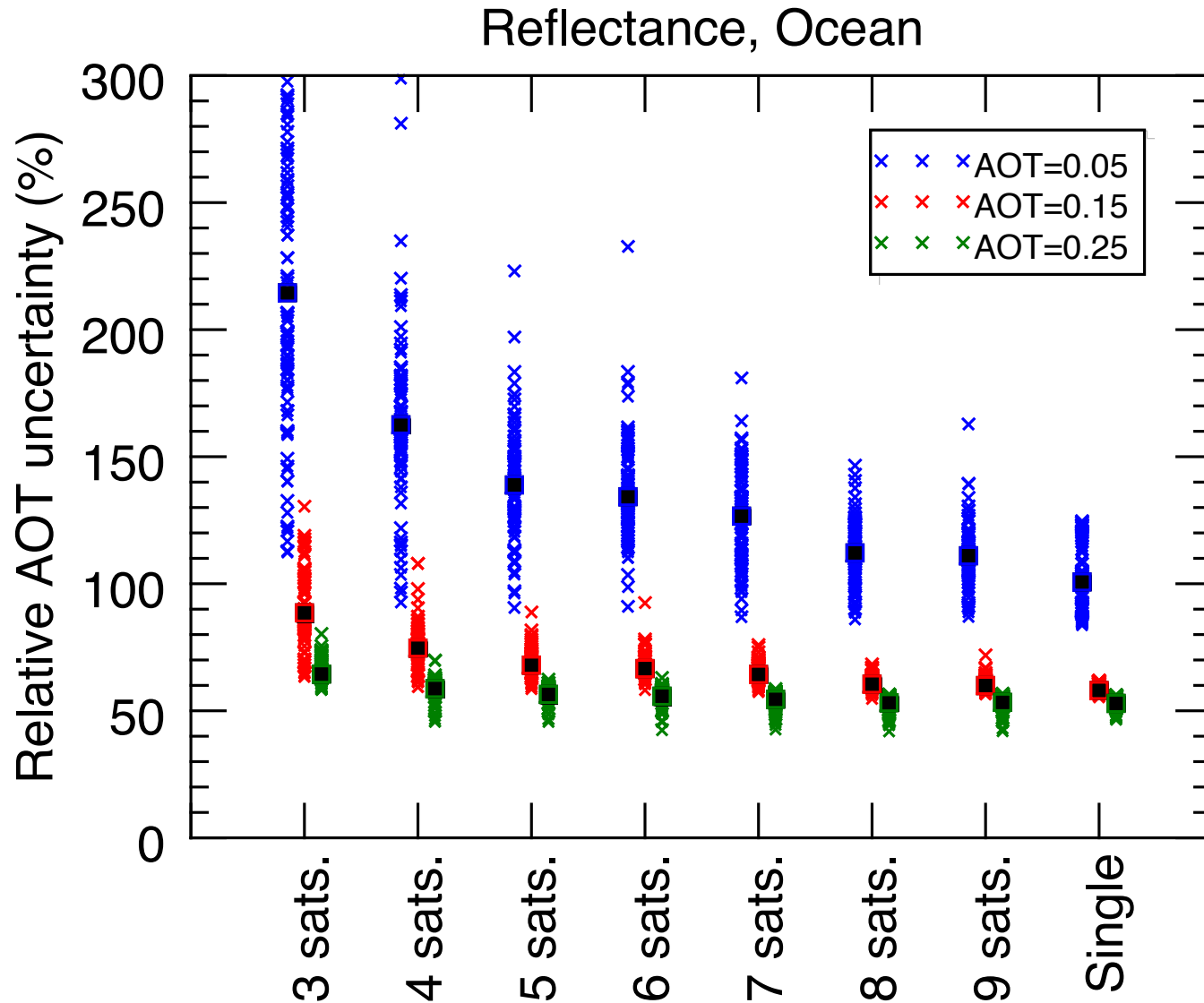
-3 -2 -1 0 1 2 3
Sensitivity in Degree of Linear Polarization, DoLP

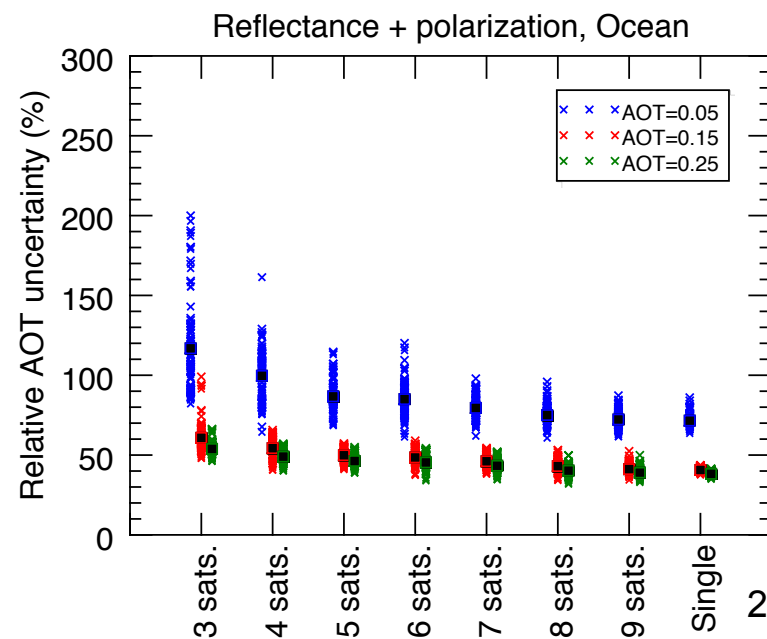
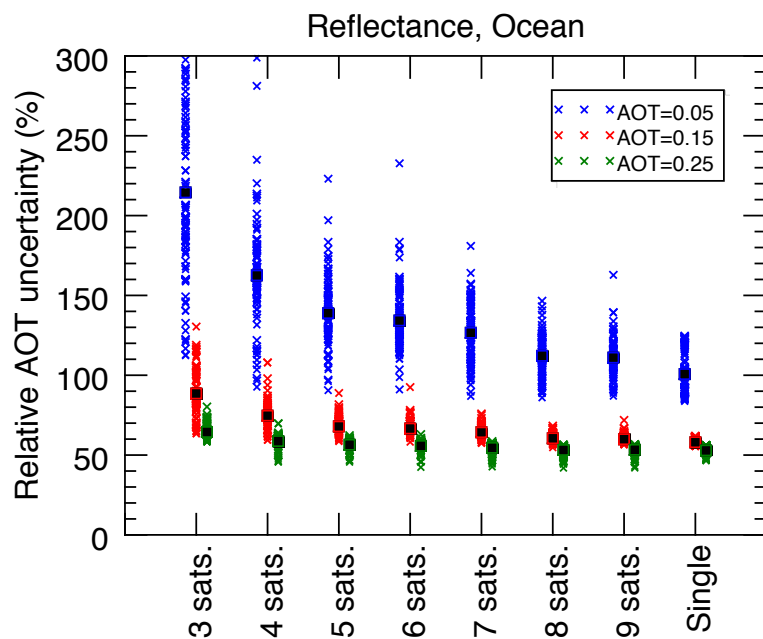
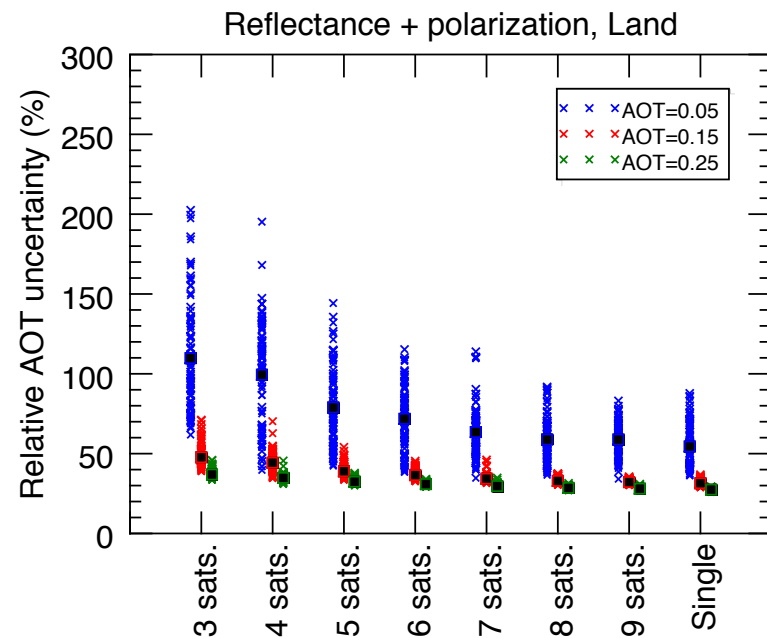
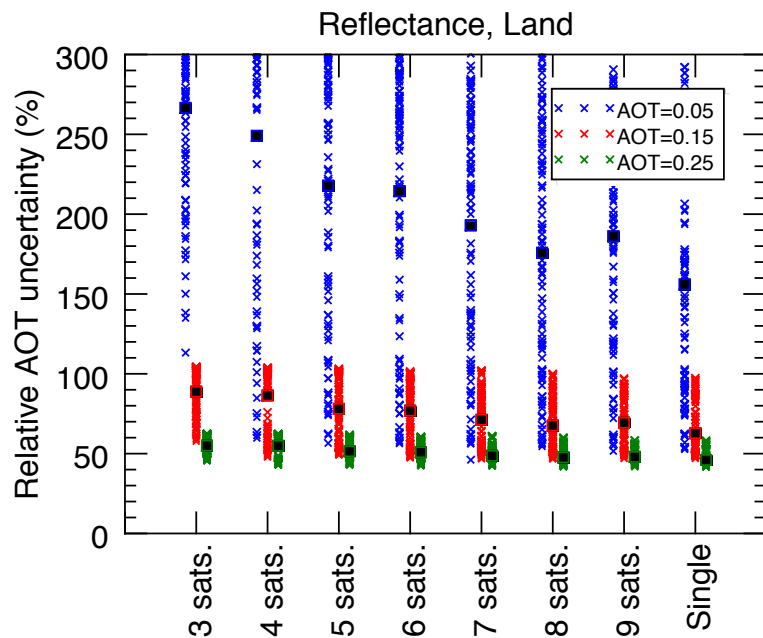
Degrees of freedom: aerosols over land, polarimeters



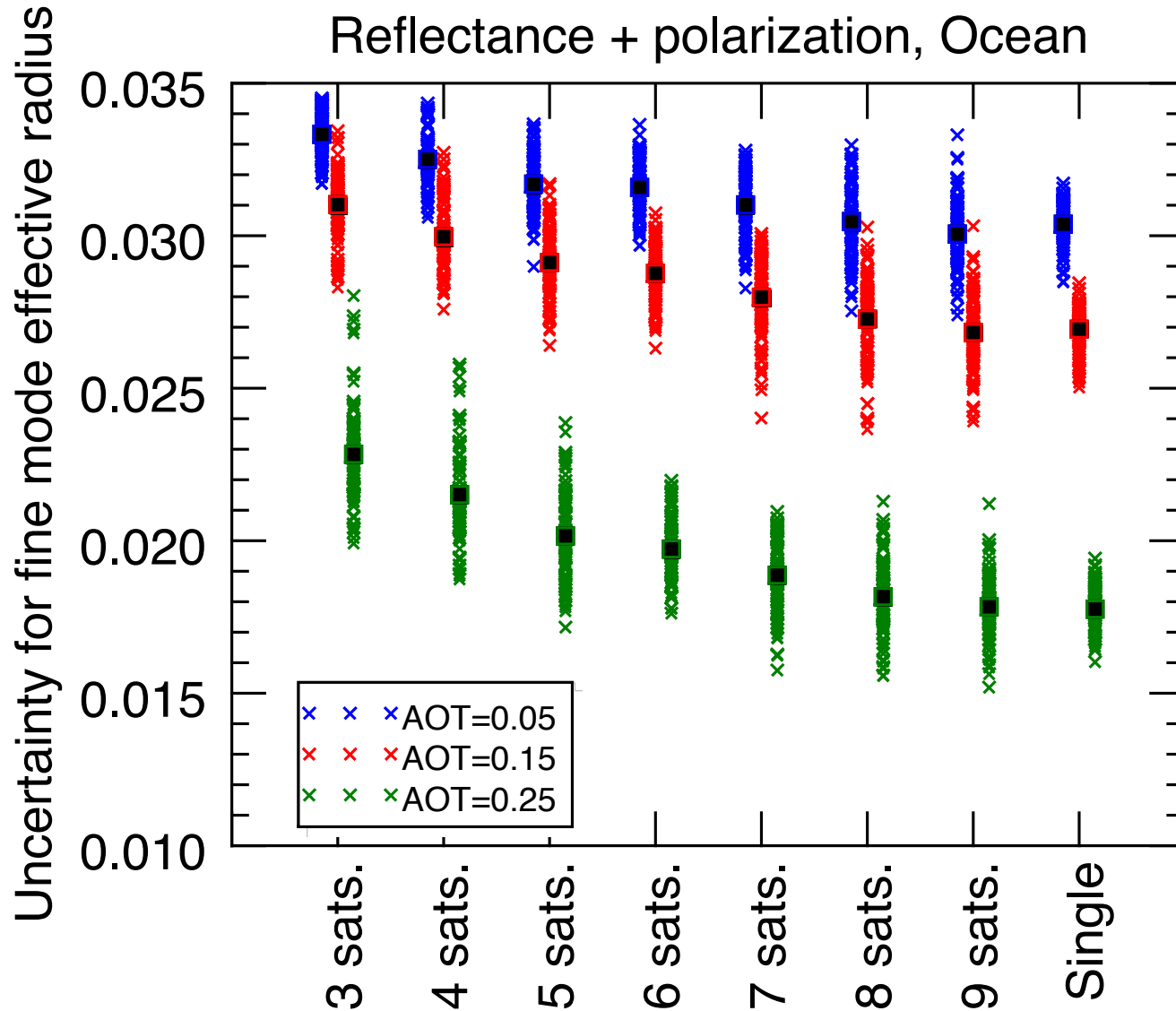


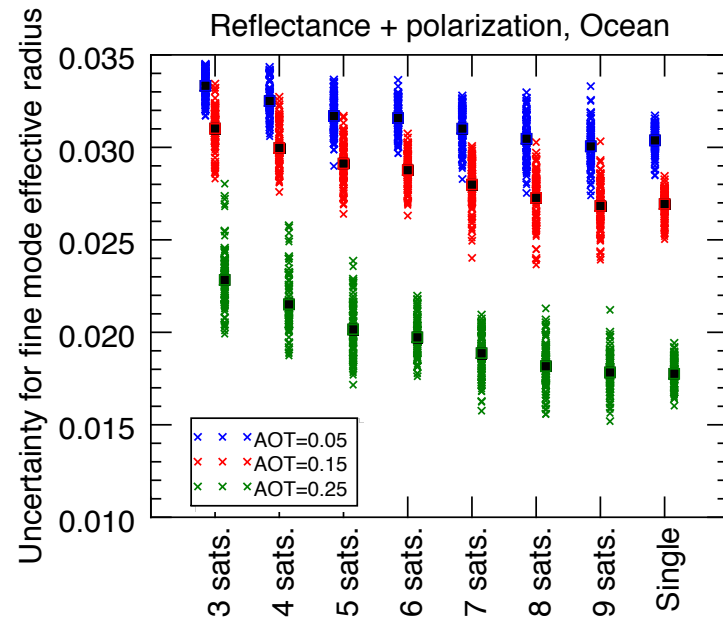
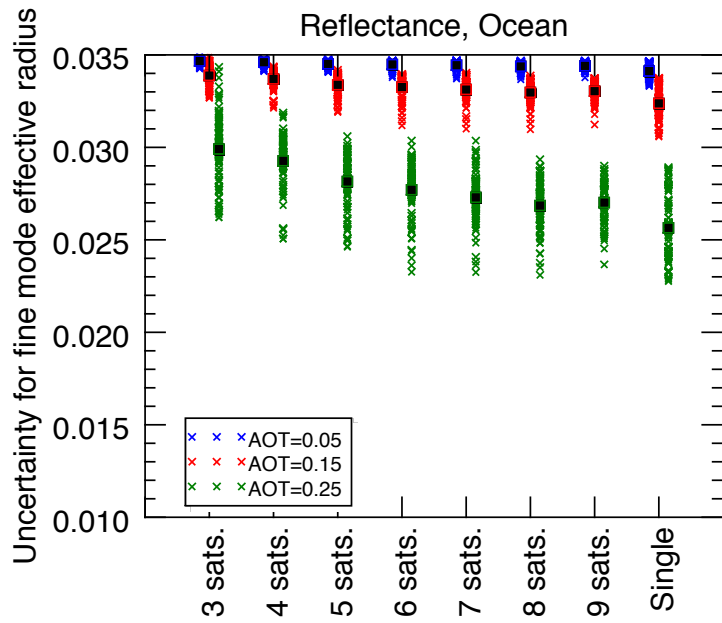
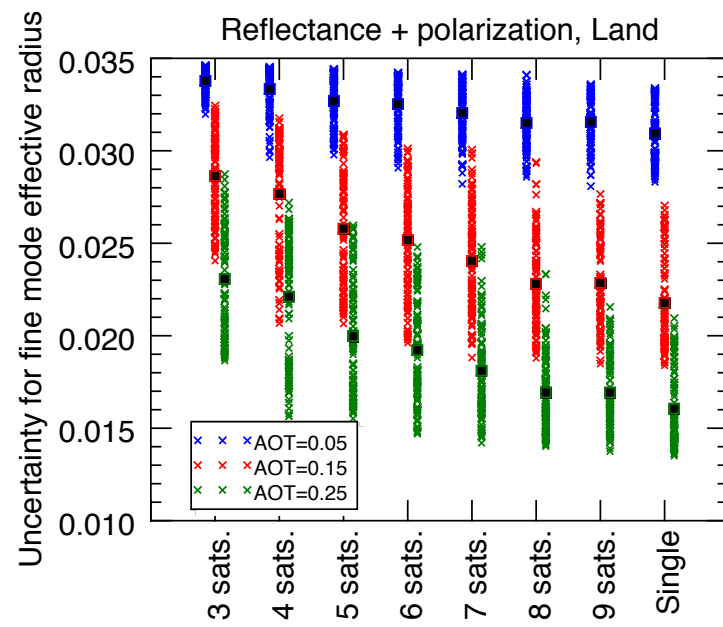
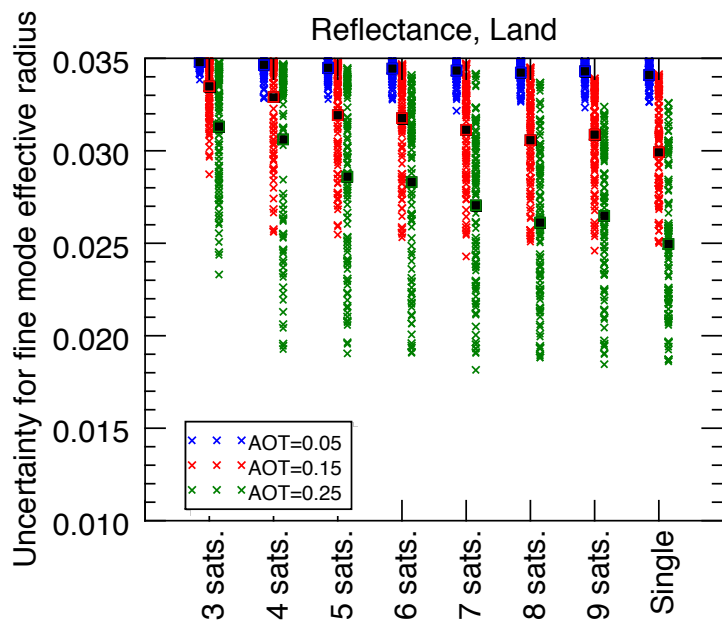
Aerosol Optical Thickness results, reflectance only





Fine mode effective radius



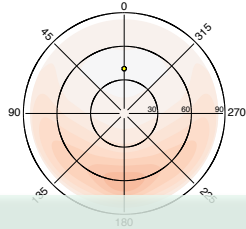


Conclusions

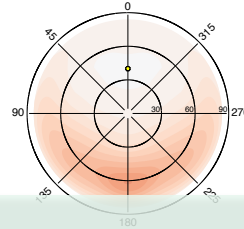
Obviously, more angles means more DoF, lower parameter uncertainty

- 9 satellites in formation \approx 9 views on a single satellite
- Improvements are gradual – loss of single observation is not catastrophic
- At some point, additional views don't improve AOT, but they do for other parameters
- Quantity of aerosols (AOT) controls ability to retrieve properties

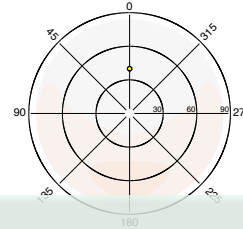
AOT(555nm) 1 type 0 Jacobian for 410nm SN0123, SZA=40, DoLP



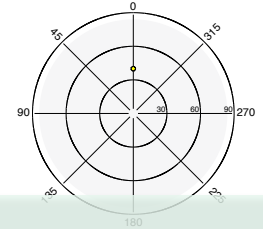
Size A, type 0 Jacobian for 410nm SN0123, SZA=40, DoLP



AOT(555nm) 1 type 1 Jacobian for 410nm SN0123, SZA=40, DoLP



Size A, type 1 Jacobian for 410nm SN0123, SZA=40, DoLP



Implications

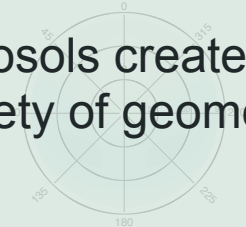
Aerosols create smoothly varying BRDF's, which can be properly sampled from a variety of geometries

This opens up possibilities for alternate observation scenarios, such as formation flight...

...many other types of tests are also needed

We have established a framework that can be used for other observations

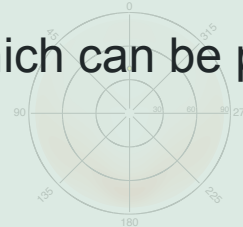
Chi Jacobian for 410nm SN0123, SZA=40, DoLP



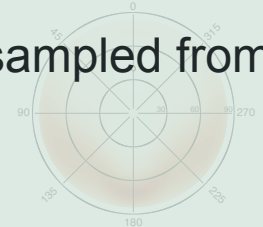
WS Jacobian for 410nm SN0123, SZA=40, DoLP



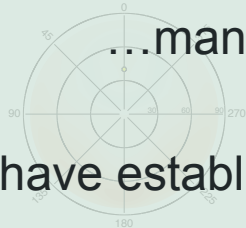
AOT(555nm) 1 type 0 Jacobian for 555nm SN0123, SZA=40, DoLP



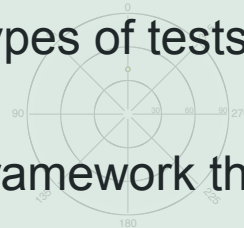
Size A, type 0 Jacobian for 555nm SN0123, SZA=40, DoLP



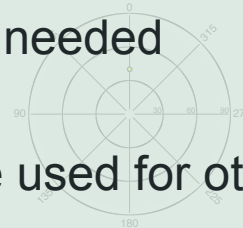
AOT(555nm) 1 type 1 Jacobian for 555nm SN0123, SZA=40, DoLP



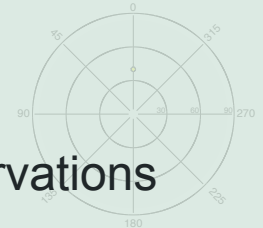
Size A, type 1 Jacobian for 555nm SN0123, SZA=40, DoLP



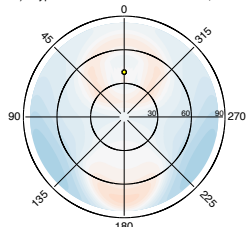
Chi Jacobian for 555nm SN0123, SZA=40, DoLP



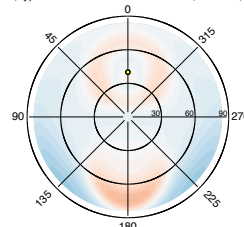
WS Jacobian for 555nm SN0123, SZA=40, DoLP



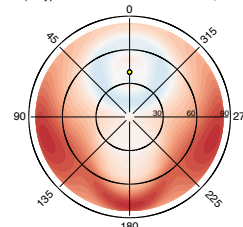
AOT(555nm) 1 type 0 Jacobian for 865nm SN0123, SZA=40, DoLP



Size A, type 0 Jacobian for 865nm SN0123, SZA=40, DoLP



AOT(555nm) 1 type 1 Jacobian for 865nm SN0123, SZA=40, DoLP



Size A, type 1 Jacobian for 865nm SN0123, SZA=40, DoLP

